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Optimization of Rotor Speed Variations in Microturbines

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Abstract

Distributed Generation (DG), and especially microturbine generation (MTG) system, plays a significant role in Smart Grids. One of the most important variables of a MTG system is the governer speed. This paper defines a problem on transient speed response of MTs for a step load. The aim is to optimize the speed governer parameters in order to minimize the transient response of MTG. Differential Evolutionary Algorithm (DEA) is employed to solve the problem. The stability issue of the MTG system is also discussed in the paper. The simulation results show the effectiveness of a fine-tuned speed governer by using the proposed method.

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Keywords: Distributed generation; Microturbine; Differential Evolutionary Algorithm; Speed response

1. Introduction

With growing power demand and increasing concern about the depletion of fossil fuel, the use of Distributed Generation (DG) resources has many commercial and technical benefits[1]. In Smart Grids (SGs), DG is one of the main parts of the demand-side power system [2]. Also, improving the smart grid stability and reliability, providing the power supply economically, energy storage and environmental considerations increase the attention to DG [3]. They have several benefits to the customers, utilities and the environment, too [4]-[8]. DGs can be widely used in SGs and their modeling and controller design is one of the main necessities of this application.

Distributed generation can have renewable technologies (such as wind turbine and photovoltaic) or recent promising non-renewable technologies (such as microturbine and fuel cell). It is widely accepted that microturbine (MT) plays and will play an important role in SGs. Their ratings provide a variety of opportunities to meet applications of distribution systems [9]-[13]. Their applications are including peak shaving, co-generation, remote power control and premium power. They are composed of turbine,

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generator, compressor, recuperator, control system and drive system. If MT is connected to distribution system, then it will affect the dynamics of the system. The transient behavior of MT system can be assessed by detailed nonlinear dynamics modeling. Thus, an accurate model of MT is necessary to analyze problems such as power quality and voltage regulations [14]. This paper is focused on this subject and it is organized, as follows: the next section reviews the modeling of MT and its control schemes. The modeling of permanent magnet (PM) generator is also presented in this section. In the section III, the problem corresponding to the transient response of MT's rotor speed (in a load step variation) is presented. Section IV discusses the optimization procedure including normalizing technique and Differential Evolutionary Algorithm (DEA). A case study is studied in section V, which shows the effectiveness of the proposed controller design method.

2. MT and PM Generator Modeling

In this section, the modeling of the MT is discussed. It is assumed that the system is operating under normal conditions, i.e., the fast dynamics of the MT including start-up, shut-down, internal faults and loss of power have not been considered.

There are two basic designs for MTs. The first one is a single-shaft design. In this design, the compressor, microturbine and PM generator are mounted on one shaft and the frequency of the generator is very high. The rectifier and inverter are essential for changing the high frequency voltage to 50 or 60 Hz voltage. The second MT design is a split or twin shaft design. The compressor and the gasifire turbine are mounted on one shaft and the power turbine and the generator are mounted on the other shaft. The power turbine is rotating at 3600 rpm usually and the generator is connected to it via a gearbox. The inverter application is not necessary in this design. The first aforementioned model, i.e., single shaft design, is studied in this paper. As shown in Fig.1, this design consists of MT, PM generator and the power conditioning system.

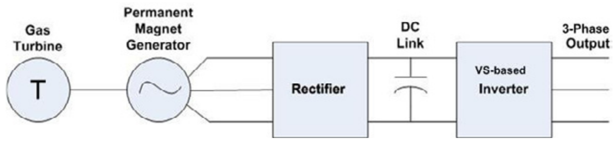

Fig. 1. Microturbine generation system

2.1. Modeling of MT

The turbine has different control systems including speed control, acceleration control, temperature control and fuel flow control.

2.1.1. Speed control system

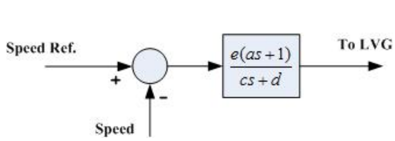

Fig. 2. Speed control system

The speed control system input is the difference between a reference speed (i.e., 1pu) and the synchronous generator rotor speed. In this paper, a lead-lag transfer function has been used for modeling the speed control system, as shown in Fig. 2. The output of this system is forwarded to LVG (low value gain), which selects the least value of its inputs.

In this figure, *e* is the controller gain, *a* is the governor lead time constant, *c* is the governor lag time constant and *d* is a constant representing the governor mode.

2.1.2. Acceleration control system

Acceleration control system should limit the rate of the rotor acceleration during turbine start-up. This control system could be neglected, if the operating speed of the system is near to its rated speed. This control system has been shown in Fig. 3.

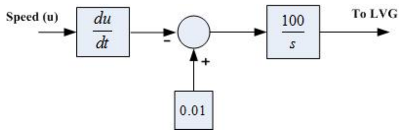

Fig. 3. Acceleration control system

2.1.3. Temperature control system

This control system limits the gas turbine output at a certain firing temperature without considering the ambient temperature or fuel specification. A thermocouple measures the temperature of the exhaust gas of the turbine resulted from burning the fuel in the combustor, and then compares it with a reference temperature. As shown in Fig. 4, if the measured temperature exceeds the reference, the difference will become negative and it will start lowering the temperature control output. In LVG, when the temperature control output becomes the lowest in comparison to the governor output and acceleration control output, the value will pass through and temperature control will run to limit the output. As a result, it reduces the fuel flow to the combustor so reduces the exhaust temperature. When one of the speed governor output or acceleration control output become the least in LVG, its output passes through and the unit gain operates on it.

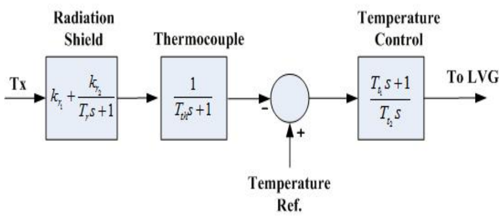

Fig. 4. Temperature control system

2.1.4. Fuel flow system

The fuel flow from the fuel system results from the inertia of the fuel system actuator and of the valve positioner. The valve positioner transfer function is, as follows [15],[16]:

$$E_l = \frac{k_v}{T_v s + c} F_d \tag{1}$$

where k_v is the valve positioner gain, T_v is the valve positioner time constant, c is a constant and F_d, E_l are input and output of the valve positioner.

The fuel system actuator transfer function is expressed by the following equation [17],[18]:

$$W_f = \frac{k_f}{T_f s + c} E_l \tag{2}$$

where K_f is the fuel system actuator gain, T_f is the fuel system actuator time constant and W_f is the fuel demand signal (in p.u). The output of LVG, V_{ce}, assigns the least amount of the fuel for the operating point. As shown in Fig. 5, it is one of the inputs to the fuel flow system. Another input to the fuel system is the turbine speed (in per-unit). The per-unit value of V_{ce} corresponds to the mechanical power of the turbine in steady state (also, in per-unit).

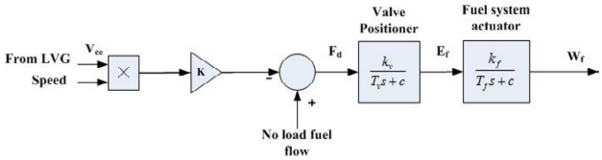

Fig. 5. Fuel flow system

The value of V_{ce} is scaled by the gain, then, delayed and off-set by the minimum amount of the fuel flow at no-load condition, to ensure the continuous combustion process in the combustion chamber.

2.2. Permanent Magnet Synchronous Generator Model

The advantages of a Permanent Magnet Synchronous Generator (PMSG) are the elimination of field copper losses, higher power density, lower rotor inertia, robust construction and higher efficiency. The disadvantages are the loss of the flexibility in the field flux control, the demagnetization possibility and higher investment cost.

The PMSG is analyzed by *dq0*-axis theory. For a balanced system, the *0*-axis is eliminated. The *dq*-axis equations are formulated, as follows [19]:

$$\frac{di_{qs}}{dt} = \frac{1}{L_{qs}}[V_{qs} - R_s i_{qs} - L_{ds}\omega_e i_{ds} - \hat{\psi}_f \omega_e] \tag{3}$$

$$\frac{di_{ds}}{dt} = \frac{1}{L_{ds}}[V_{ds} - R_s i_{ds} + L_{qs}\omega_e i_{qs}] \tag{4}$$

$$T_e = \frac{3P}{4}[\hat{\psi}_f i_{qs} + (L_{ds} - L_{qs}) i_{qs} i_{ds}] \tag{5}$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_{shaft}) \tag{6}$$

where ω_e and ω_r are the electrical and mechanical angular velocities of the rotor (in rad/sec), V_{qs} and V_{ds} are the q and d axis voltage components, I_{qs} and I_{ds} are the q and d axis current components, L_{qs} and L_{ds} are the q and d axis inductances of the stator, ψ_f is the flux linkage induced by the permanent magnets of the rotor in stator phases, J is the inertia of the rotor (kgm^2), T_{shaft} is the shaft torque produced by the microturbine (N.m), T_e is the electric torque generated by the PMSG (N.m) and P is the number of poles. It is worth to mention that T_e and T_{shaft} are negative or positive for generator or motor operation modes, respectively.

2.3. Power conditioning system

The power electronic converter converts the high frequency AC power of PMSG to DC and then to 60 (or 50) Hz AC. It is used to control the frequency of the output power of MT. It controls the inverter output voltage magnitude and angle and maintains the output voltage frequency at a prescribed level. It is also consist of a voltage source inverter and LC filter to reduce the harmonic distortion and improve the power quality [20]. In this type on converters, a PI voltage regulator, based on *abc* to *dq* and *dq* to *abc* transformations, is used to regulate the load voltage at 480 V. The output of the voltage regulator is used to generate PWM gate pulses.

3. Objective Function

The two most important variables of a MT system are the fuel consumption and the rotor speed. In practice, it is important to have suitable transient response (minimum rotor speed variation) against load changes. The minimum overshot and settling time are usually considered to evaluate the speed transient response. Furthermore, the issue of the stability of the MT system is also considered in this way. In fact, if this criterion reduces intensively, the system will go through the instability condition and the result will be automatically evaluated as undesirable one.

In this paper, the Differential Evolution Algorithm (DEA) is used to optimize the parameters of the speed governer control system shown in Fig.2.

It is supposed to achieve the best speed transient response. As it is possible to change the parameters of controllers during the operation, then, it is possible to prepare a look-up table and implement the proposed control method for different load changes such as a 24-hour load.

One sample load change from $0.72\ P_0$ to $0.64\ P_0$ (when P_0 is the daily peak), has been applied to MT simulated system. The simulation results have been shown in Fig. 6. In the simulations, the load change is applied at $t=10s$ and the simulation time is 5 seconds. In this case, the parameters of the speed governer are $a=0.9$, $c=0.1$, $d=0.5$ and $e=52$. As shown in Fig.6, the speed variable has unacceptable transient response to the load change and oscillates a lot when the speed governer system has not been adjusted appropriately.

In the proposed method, the object is the speed transient response improvement after a step load change.

The total speed deviation of the speed after a step load change is defined, as follows:

$$x = \int_{t_0}^{t_0+T} \left| \omega(t) - \omega_T \right| .dt \qquad (7)$$

where t_0 is the time of load changing, T is the duration of transient period or the start time of a steady state condition, $\omega(t)$ is the speed function and ω_T is the speed in the steady state condition. For example, t_0 is 10s and $T=5s$. The minimization of x means the minimization of the shaded area in Fig .6.

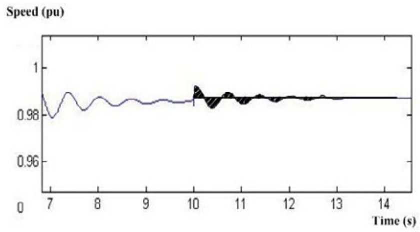

Fig. 6. Speed and total fuel consumption in poor-controlled MTG system. (For controller with a=0.9, c=0.1, d=0.5 and e=52)

Thus, the best parameters of the speed governer for the objective function can be obtained.

3.1. Differential Evolutionary Algorithm

In this section, Differential Evolutionary Algorithm (DEA) is presented. DEA is a simple population based, stochastic parallel search evolutionary algorithm for global optimization and is capable of handling non-differentiable, nonlinear and multi-modal objective functions [21] that attacks the starting point problem by evaluating the objective function at multiple random initial points. A population composed of *NP* individuals evolves over several generations to reach an optimal solution. In the next section, the application of DEA to the proposed problem will be discussed. The main idea of DEA is illustrated in Fig. 7. It includes several steps, which are explained in the following sub-sections.

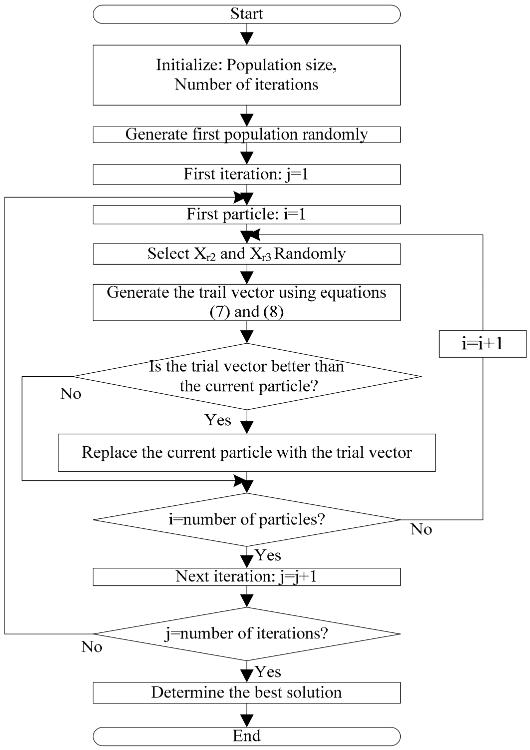

Fig. 7. Main idea of DEA

3.1.1. Initialization

The first generation consists of a population of *NP* vectors with dimension *D*, while *D* is the number of control variables. Therefore, the population individuals will be in the following form:

$$x_i = [x_1, x_2, ...] \tag{8}$$

In the initialization process, a lower bound $x_{j,min}$ for each variable as well as an upper bound $x_{j,max}$ are determined as described in section III.A of the paper. Once the initialization of bounds is specified, a random number generator assigns a value for each vector within the prespecified range. For example, the initial value of the j^{th} variable of the i^{th} vector is, as follows:

$$x_{i,j} = rand(0,1).(x_{j,\max} - x_{j,\min}) + x_{j,\min} \tag{9}$$

3.1.2. Fitness evaluation

The goal of the optimization is to minimize the objective function. However, this optimization is along with the satisfaction in several constraints. Since the constraints of this problem are implied on particle variables, one usual solution to meet the constraints is to consider them during the solution process. This is described in the section 6 of this section.

3.1.3. Determining global best individual

In each iteration of DEA, a comparison among individuals is made to determine the best solution (particle) x_{best}. To specify the x_{best}, all the members of the current generation need to compete with each other. For the first generation, x_{best} is the best one in the initial population. For the *k-th* generation, $x_{best,k}$ is obtained and compared with the last global best individual x_{best}. If the $x_{best,k}$ is better than x_{best}, it takes x_{best} place; otherwise x_{best} remains unchanged.

3.1.4. Mutation

In DEA, a mutant vector is produced from each individual. This step can be described, as follows:

$$\mathrm{V}_{i,K+1} = X_{best} + F.(X_{r2,K} - X_{r3,K}) \tag{10}$$

where $X_{r2,G}$ and $X_{r3,G}$ are randomly chosen vectors (particles) among the population in the generation *K*, *F* is a constant within (0, 2) and $V_{i,K+1}$ is the trial vector. If $X_{r1,K}$ is replaced by $X_{best,K}$, another form of DEA called BDE will be formed. In this paper, BDE had better results than the conventional DEA and *F* is set to 0.5.

3.1.5. Cross-Over

In this step, the following equation is used to determine the trial vector that may replace the current vector in the next population with the probability of the cross-over constant (CR), which is between 0 and 1 [22]:

$$U_{i,j,k+1} = \begin{cases} V_{i,j,k+1} & if\ \ rand(0,1) \le CR\ \ or\ \ j = i \\ X_{i,j,k+1} & otherwise \end{cases} \tag{11}$$

where *rand(0,1)* is a random number generated within the range of 0 and 1 and *CR* is the cross-over rate set to 0.5.

3.1.6. Handling Constraints

To ensure that all the variables of trial vector are within their limits, the following procedure is performed:

$$\begin{aligned} &If\ \ U_{i,j,k+1} > x_{j,\max} \quad then \quad U_{i,j,k+1} = x_{j,\max} \\ &If\ \ U_{i,j,k+1} < x_{j,\min} \quad then \quad U_{i,j,k+1} = x_{j,\min} \end{aligned} \tag{12}$$

3.1.7. Selection

Finally, like other evolutionary algorithms, the selection phase is performed and the generated vector is tested comparing with the best vector of prior iteration. If the trial vector results in a better fitness function than the current particle, it will take the current particle's place. If not, the current one stays.

In BDE, these steps are repeated in times of a defined number of iterations and the algorithm is terminated if the stop circumstances are confirmed.

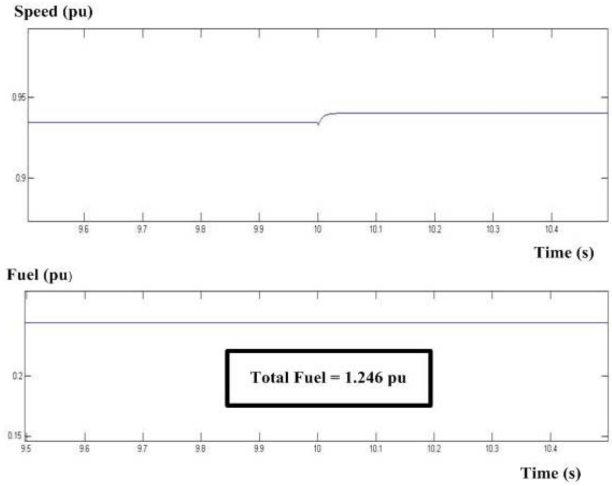

Fig. 8. Speed and total fuel consumption for speed weighted optimal control.

3.2. Implementation of normalizing technique and DEA in speed governor design

In initialization step of DEA, the population individuals vector will contain the parameters of the speed governer system:

$$x_i = [a, c, d, e] \tag{13}$$

where *a, c and d* are the parameters of the speed control system and *e* is the gain of speed governor system.

The optimization is run to find optimized parameters of the speed governor system (a, c, d and e) that the speed variable is at its best condition. In other words, as shown in Fig.8, the speed variable is almost without variations after load change. In this case, the parameters of the speed governer are a=0.72, c=0.23, d=0.7 and e=34.

4. Simulation Results

The system that is assumed to be analyzed includes turbine and its controllers, permanent magnet synchronous machine and power conditioning models. The modeling is described in section I. The parameters of different part of the system are reported in table I and II. The load change which the controller is designed for it is described in section III. There is the possibility for the modern controllers with the ability of parameters changing to have a look-up table for 24-hour load changes and optimize the parameters simultaneously.

Other important output of a MT system is total fuel consumption that can be analyzed in this method. In order to verify the proposed approach, in table III, the results of the different weighting factor of the objectives are presented. The quality of the objectives are varied correspond to the weighting factors which are allocated to them. Several simulations result that the weighting factors in bold column are the most suitable ones for speed transient response and will proposed the optimized parameters of the speed governer.

Table I: Parameters of PMSG

Parameter	Value
R_s	2.875 Ohm
No.of.poles	4
L_d,L_q	8.5 mH
λ	0.10396 wb

Table II: Load parameters

Parameter	Value
Rated Power	50 kW
Rated Voltage	480 Vrms
Frequency	50 Hz

Table III: Simulation result for different weighting factors

Weighting factor	Total fuel consumption factor (C1)	1	1	0.1	0
	Speed variation factor (C2)	0	1	1	1
Total fuel consumption (pu)		0.8283	0.839	0.9684	1.2456
Speed variation (pu)		2.539	0.589	0.0026	1.456×10^{-6}

5. Conclusions

Main outputs of a microturbine system are fuel and speed. The important factors that are mainly considered to evaluate these two outputs are total fuel consumption and speed variation after load changing during the daily demand. Load changing makes different effects on these two outputs. The speed governor system affects the fuel and speed specification. In this paper, we consider speed transient response as the most important output to be optimized. Thus, an optimization based on differential evolutionary has been applied to the system to find the best controller parameters in order to have the most suitable specification for speed variation after load change. The results showed that the fuel consumption is also in appropriate condition in different weighting factor allocated to it against speed variation. Therefore, the most suitable speed governor system has been designed in the biggest weighting factor condition for speed, and the least total speed variations against daily load changing besides suitable fuel consumption condition has been obtained.

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